Run II Emittance Preservation

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Talk outline

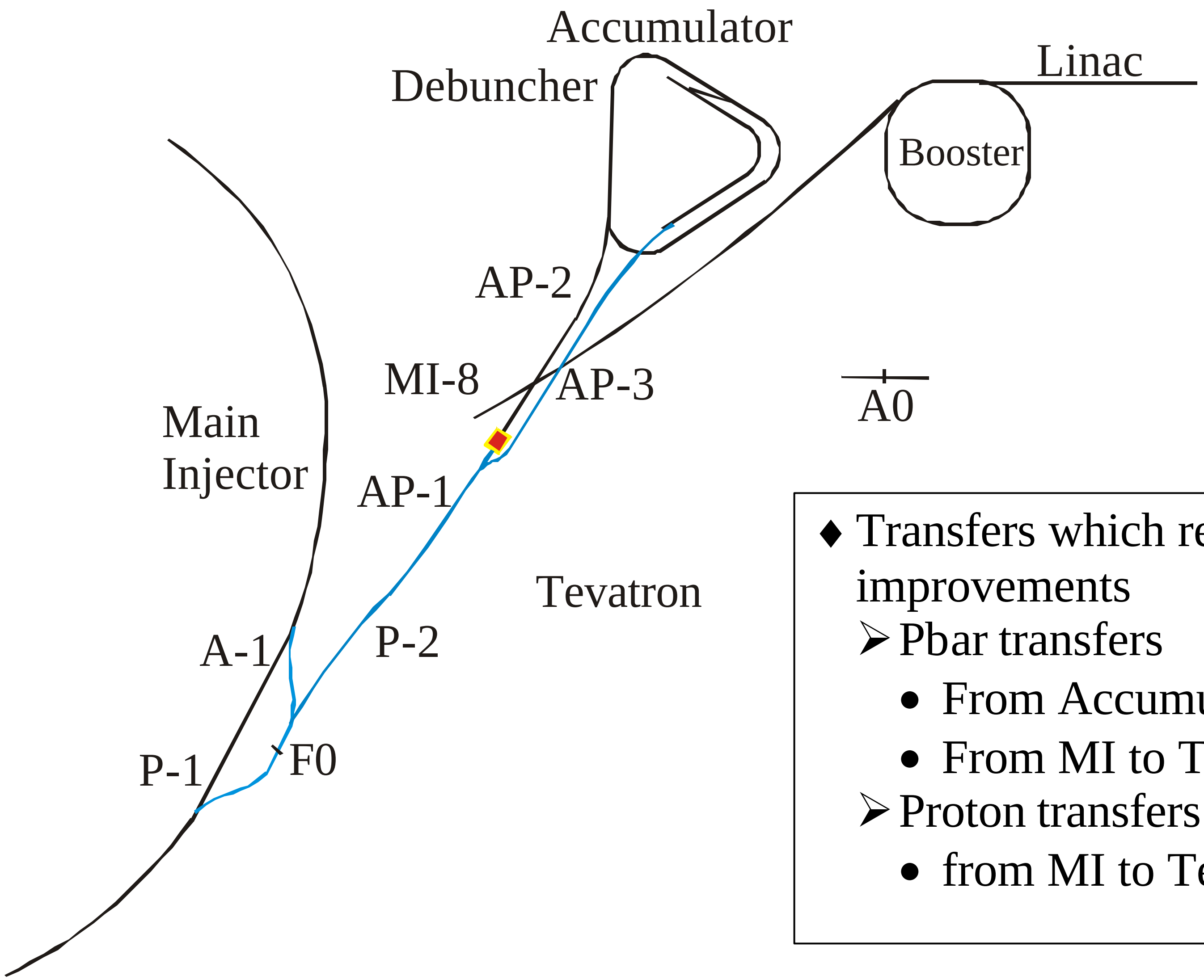
1. Sources of emittance dilution
2. Beam transfers
   a. Injection errors
   b. Optics mismatch
3. Luminosity lifetime

   Conclusions

1. Sources of the Emittance Dilution

- **Emittance growth is irrecoverable and all the means need to be applied to prevent it**
  - No antiproton beam cooling after the beam leaves accumulator
  - No cooling for proton beam
- **Emittance growth reduces initial luminosity and, consequently, integrated luminosity**
  - due to beam size increase
  - due to intensity loss related to scraping particles with large amplitudes
- **Emittance preservation requires**
  - Prevention emittance growth during beam transfers
    - Prevention/suppression of the emittance growth due to injection errors
      - Turn-by-turn measurements position measurements for every injected bunch are used to close the orbit
      - Injection dampers
    - Careful optics design and measurements to prevent emittance growth due to optics mismatches
  - Prevention emittance growth at beam acceleration
    - Tune and chromaticity control
  - Prevention/Reduction of the emittance growth during store
    - Gas scattering
    - Noises affecting the beam (RF, kickers, *et. c*.)
    - IBS scattering
    - Beam-beam effects

2. Beam Transfers



The layout of transfer lines

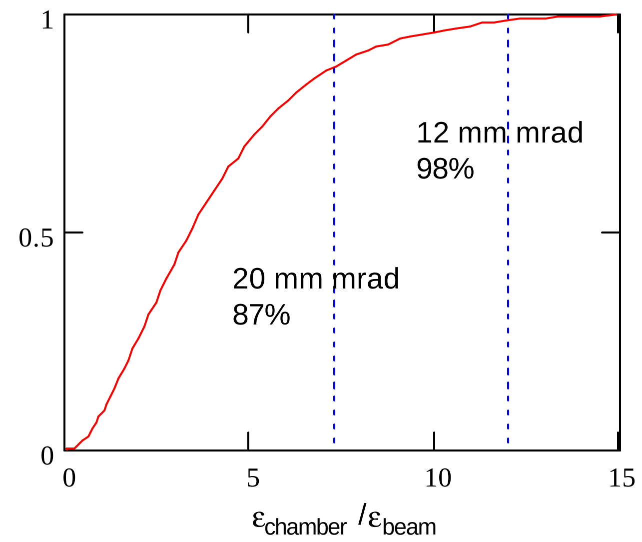
- ♦ Transfers which require further improvements
  - ➢ Pbar transfers
    - From Accumulator to MI, 8 GeV
    - From MI to Tevatron, 150 GeV
  - ➢ Proton transfers
    - from MI to Tevatron, 150 GeV

Status and projections for the beam transfers

	Line	Energy [GeV]	March 2003		Goal (~June 2003)	
			$\varepsilon_{in} / \varepsilon_{fin}$ * [mm mrad]	Transfer efficiency	$\varepsilon_{in} / \varepsilon_{fin}$ * [mm mrad]	Transfer efficiency
Accumulator to MI, $\bar{p}$	AP3-P1	8	6 / 8	97%	7** / 8	>99%
MI to Tevatron, $\bar{p}$	A1	150	10/17	99%	10 / 12	99%
MI to Tevatron, p	P1	150	21/24	99%	21 /23	99%

* $\varepsilon \equiv (e_x + e_y)/2$; ** 170 mA pbar stack;

- Pick luminosity rises with emittance decrease due to
  - Smaller beam size at collisions
  - Beam current increase due to increase of beam life time at the injection and top energies
    - Reducing pbar emittance in the Tevatron from ~20 mm mrad to ~12 mm mrad should decrease pbar loss at acceleration and squeeze from ~10-12% to 1-2%
- Presently, major contribution to the antiproton beam emittance growth comes from the beam transfers



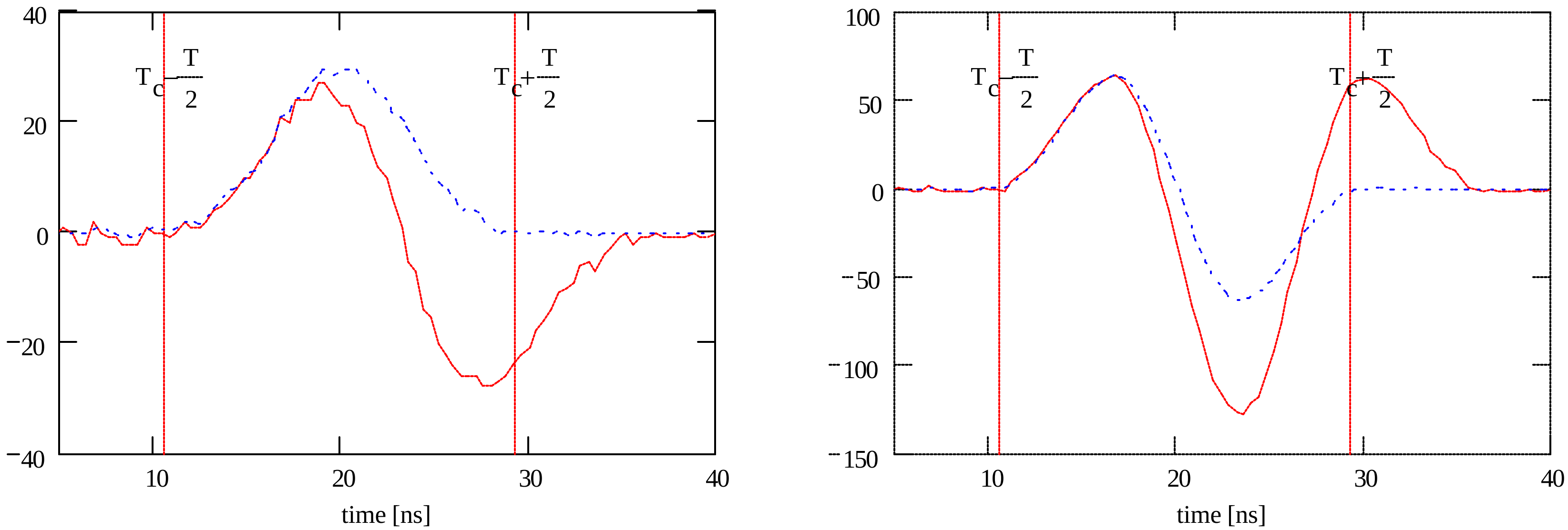
Emittance Growth due to Injection Oscillations

	Present performance		Goal		
	A_x/A_y [mm]	$\Delta\varepsilon_x/\Delta\varepsilon_y$ [mm mrad]	A, [mm] no damper	A, [mm] with damper	$\Delta\varepsilon$ [mm mrad]
Accumulator to MI, $\bar{p}$	1 – 2	0.5 – 2	< 0.7	3	< 0.25
MI to Tevatron, $\bar{p}$	0.5 – 1	1.2–4.7/ 1.9–7.7	< 0.25	1.5	< 0.5
MI to Tevatron, p	0.25–0.5	0.3–1.2/0.48–1.9	< 0.25	1.5	< 0.5

- **Sources of injection oscillations**
  - Initial injection errors
  - Shot-to-shot field variations in dipoles, dipole correctors and kickers
  - Bunch-to-bunch field variations in correctors for both pbar transfers
- **Ways to implement good quality of transfers**
  - Orbit closure before colliding bunches are injected
  - Orbit closure correction for every new injection
    - Tevatron injection dampers should come in April-May 2002
- **Turn-by-turn BPM measurement for every injected bunch confirms transfer quality**
  - 3 types of Beam Line Tuners (BLT) were tested before we come up to the final choice
  - Old Run I BLT
  - BLT based on a digital receiver
  - **BLT based on the fast (0.4 ns/sample) digital scope – is a final choice**

♦ Complications of BLT(BPM) turn-by-turn signal analysis come from interplay of

- effects of chromaticity
- and close lengths of the bunch and BLT plates



- Numerical deconvolution of digitized BLT signals create simple and reliable way to compute bunch center of gravity
- In addition to the standard beam position the digital scope data represent internal motion in the bunch

Optics Mismatch

- Types of possible optics mismatch
  - Betatron functions mismatch
  - Dispersion mismatch
  - Mismatch due to coupling
  - Optics changes for antiprotons due to long-range beam-beam effects
- Pbar transfers from MI to Tevatron exhibit significant emittance growth
  - Round trip emittance measurements (MI→Tevatron→MI) are the most reliable.

    They yield

    $\Delta\varepsilon_x \sim$ 5-8 mm mrad, horizontal

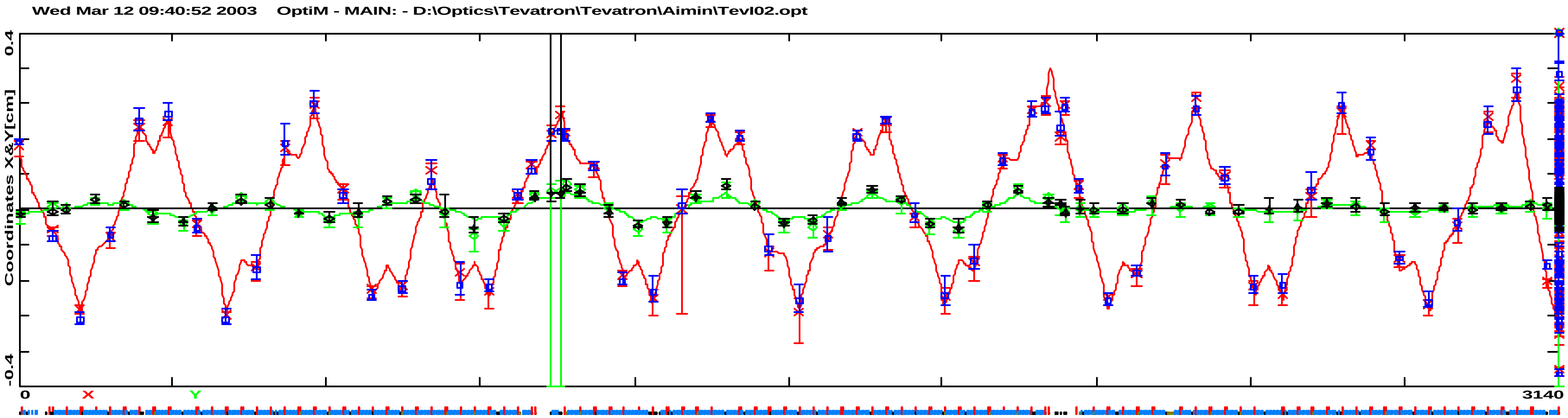
    $\Delta\varepsilon_y \sim$ 3-5 mm mrad, vertical

    - All indirect indications point to the A1 line transfer as a major problem
  - The reason of the emittance growth is still not 100% clear
    - Optics for A1 line was corrected, measured and is believed not to be a problem
    - Initial injection oscillations contribute only fraction of the measured increase
    - Tevatron optics and coupling is still not fully understood
      - Optics measurements at central orbit and their analysis were carried out
        - A number of optics problems has been discovered
        - but the difference with the design model is sufficiently small and cannot explain the observed emittance growth
      - Optics measurements at pbar helix will be acquired within a week
        - It is expected that optics at pbar helix is quite different from the central orbit optics and this is a major source of the problems

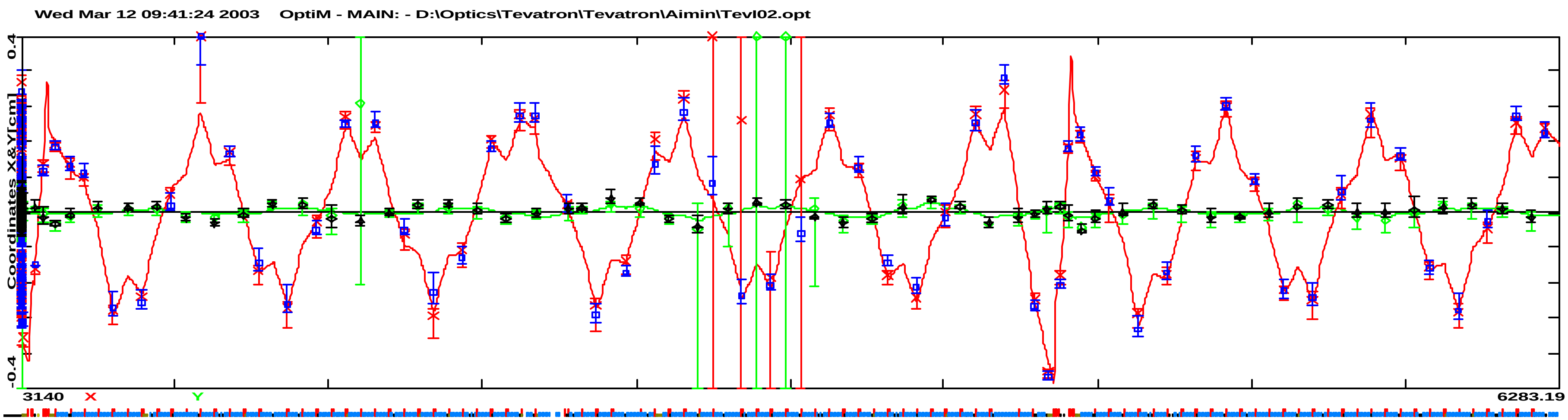
Tevatron optics measurements

150 GeV, central orbit, data were taken at Feb.20. 2003

X1: HE42 = 50 mrad



E0 F0 A0



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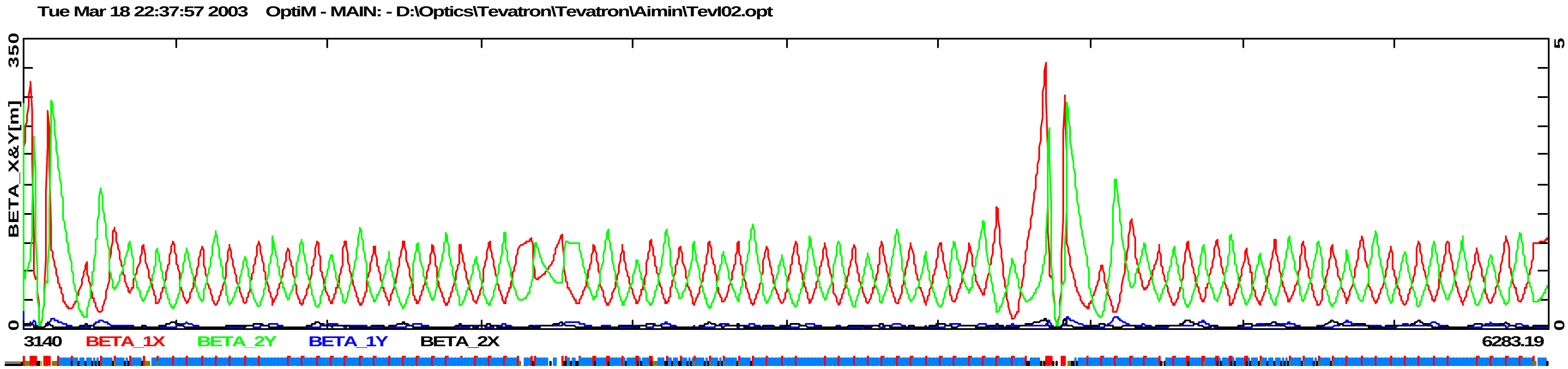
- Altogether five differential orbits are acquired (4 correctors and energy change)
- Fitting to measurements yields reliable model of the machine



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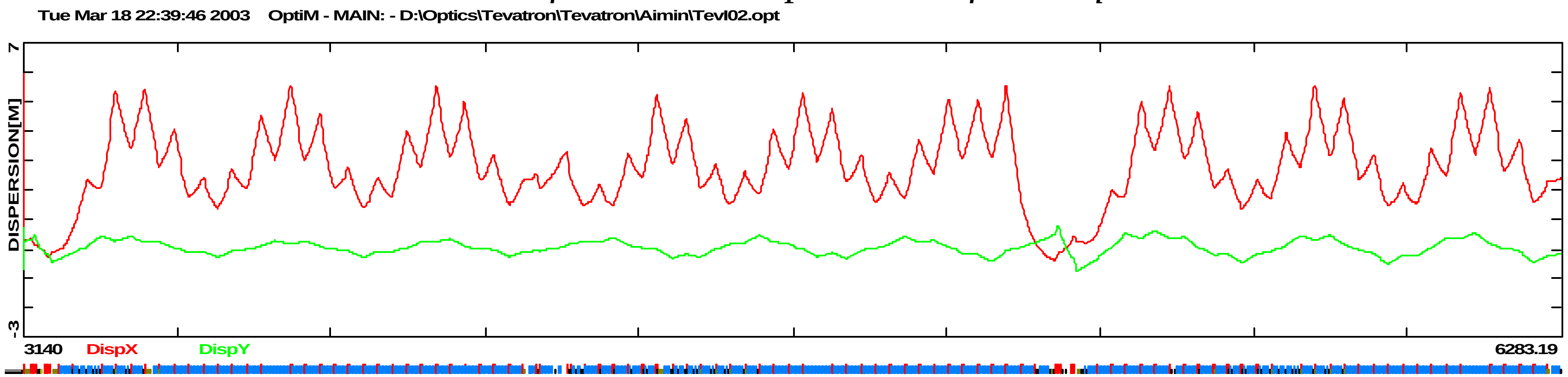
4D beta-functions and positions of skew-quads



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Dispersions

Skew-quad term in dipoles ($\Delta B/B \approx 5.7\cdot 10^{-5}$ at 1 cm) is the main source of Tevatron coupling

- It originates from the drowning of the SC coil relative to the iron core

Fudge factors and rolls to fix linear optics

Global corrections

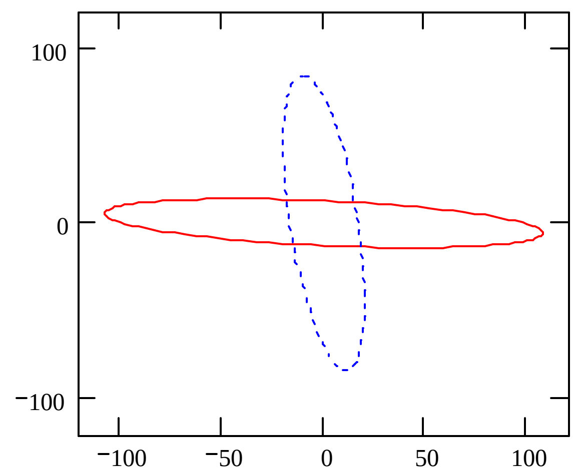
- $F_bendq = 2%; correction of dipole edge focusing
- $F_mq = 0.165%; correction of main bus quad focusing
- $F_Dskew = 1.44 units; skew quadrupole field of main dipoles

Point like corrections of quadrupole focusing

- $F_qA0U = 1%; related to beam displacement in A0
- $F_qC27 = -2%
- $F_CQ7= 20%; that corresponds to 4.4% correction for regular main bus quad
- $F_B0Q3F = 0.37%
- $F_D0Q3F = 0.6%;
- $F_D0Q2D =1%;

Quad rolls

- $Qroll_A0U = 0.5 deg; related to beam displacement in A0
- $Qroll_B0Q7= -4 deg;



Betatron modes at the BLT location

Conclusions for BPMs

- T:VPF0LU and T:VPF0LD are swapped
- T:HPF0LU and T:HPF0LD are swapped
- T:HPC28 has wrong polarity
- T:HPB22 has large noise and incorrect differential position
- T:VPC21 , T:HPC22 and T:HPC36 have large difference for positive and negative bumps. Probably there is large beam offset in BPM.

3. Luminosity Lifetime

The model takes into account the major beam heating and particle loss mechanisms

- **Phenomena taken into account**

  ⇒ Interaction with residual gas

  - ♦ Emittance growth due to electromagnetic scattering
  - ♦ Particle loss due to nuclear and electromagnetic interaction

  ⇒ Particle interaction in IPs (proportional to the luminosity)

  - ♦ Emittance growth due to electromagnetic scattering
  - ♦ Particle loss due to nuclear and electromagnetic interaction

  ⇒ IBS

  - ♦ Energy spread growth and emittance growth due to multiple scattering

  ⇒ Bunch lengthening due to RF noise

  ⇒ Particle loss from the bucket due to heating of longitudinal degree of freedom

- **Phenomena ignored in the model**

  ⇒ Beam-beam effects

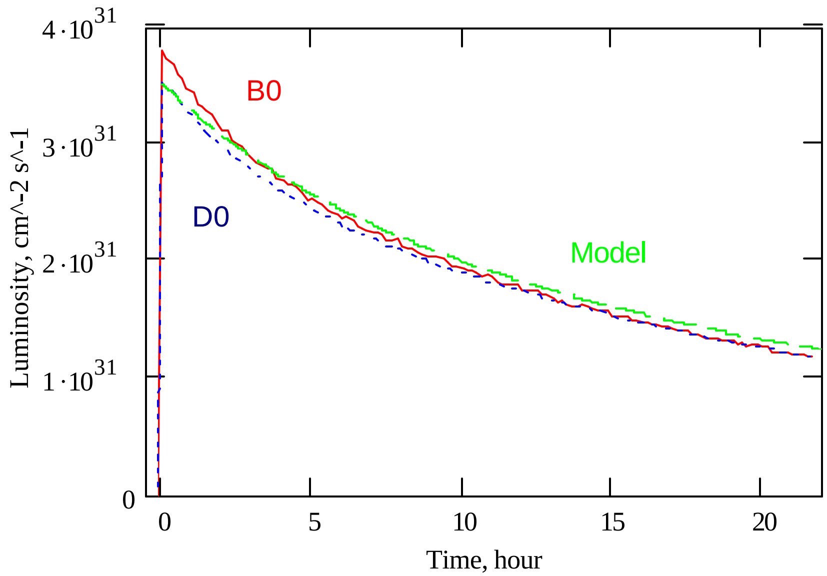
  ⇒ Non-linearity of the lattice

  ⇒ Diffusion amplification by coherent effects

- Thus, it can be considered as **the best-case scenario**

  ⇒ It describes well our best present stores

Comparison of the Model Predictions to the Store 1953 parameters



$\varepsilon n_{px}\cdot 10000 = 19$ mm mrad

$\varepsilon n_{py}\cdot 10000 = 19$ mm mrad

$\varepsilon n_{ax}\cdot 10000 = 18$ mm mrad

$\varepsilon n_{ay}\cdot 10000 = 18$ mm mrad

$\kappa = 0.3$

$\dfrac{\tau_{gas}}{3600} = 300.087$ hour

$d\varepsilon dt_{gas} = 0.168$ mm mrad/hour

$\sqrt{d\phi 2dt_{RF}\cdot 3600} = 0.016$ rad/hour$^{1/2}$

$N_p = 1.6\times 10^{11}$

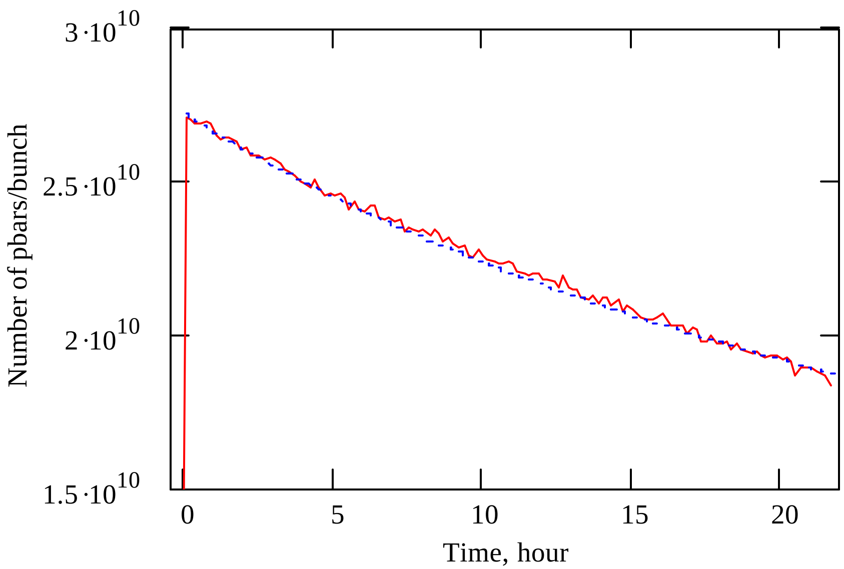
$N_a = 2.72\times 10^{10}$

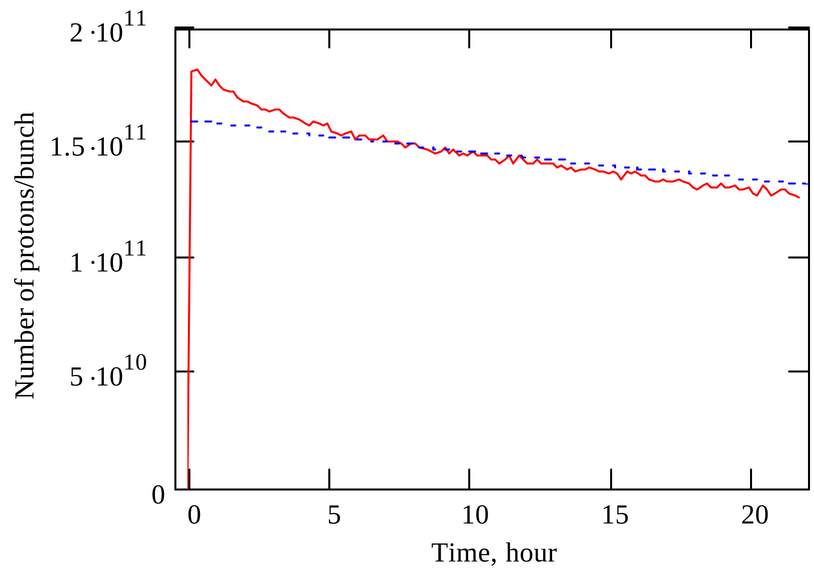
$\sigma s(\sigma_{pp}) = 59.4$ cm

$\sigma s(\sigma_{pa}) = 55.112$ cm

$Lum_0 = 3.513\times 10^{31}$

$\tau_{Lum_1} = 13.826$ hour





Conclusions

- Injections errors have been a leading reason of the antiproton beam emittance growth
  - Introducing turn-by-turn measurements for every bunch injected into Tevatron allowed us to improve orbit closure. That yielded significantly improvement for beam transfers
  - Further improvements are expected after commissioning of Tevatron injection damper (April 2003)
- First optics correction in A1 line brought better transfers and luminosity increase
  - Optics corrections and Tevatron, A1 and P1 lines are expected to produce further reduction of the beam emittances
- Significant progress in understanding of luminosity lifetime has been achieved
  - The model predicts that
    - IBS is major mechanism for emittance dilution and beam current reduction
    - There is no other than IBS and major heating mechanisms limiting Tevatron performance
      - Further improvements of Tevatron vacuum and RF noise will not yield significant improvements in integrated luminosity

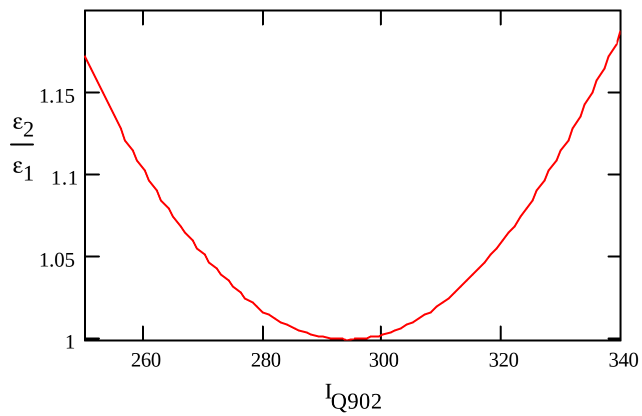
Emittance Growth due to Betatron and Dispersion Mismatch

Emittance growth from a lattice with β_1, α_1, D_1 and D_1' to a lattice with β_2, α_2, D_2 and D_2' is

$$\varepsilon' = \frac{\varepsilon}{2}\left(\frac{\beta_1}{\beta_2}\left[1+\alpha_2^{\;2}\right] + \frac{\beta_2}{\beta_1}\left[1+\alpha_1^{\;2}\right] - 2\alpha_1\alpha_2\right) + \frac{\sigma_p^{\;2}}{2}\left(\beta_2\left(D_0' - D_1'\right)^2 + 2\alpha_2\left(D_0' - D_1'\right)\left(D_0 - D_1\right) + \frac{\left(D_0 - D_1\right)^2}{\beta_2}\left(1+\alpha_2^{\;2}\right)\right)$$

Emittance growth due single quad focusing error at zero dispersion

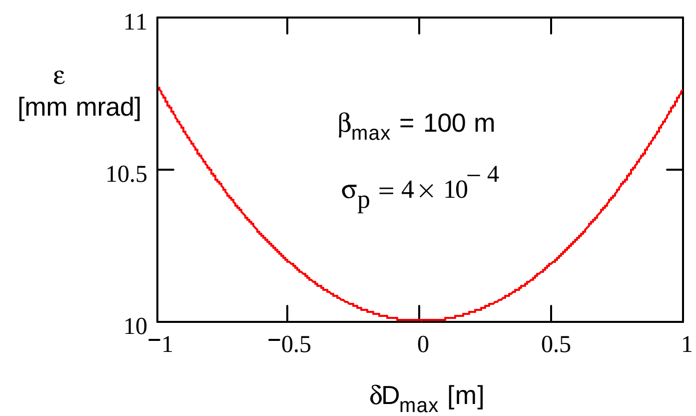
$$\varepsilon_2 \approx \varepsilon_1\left(1 + \frac{\delta\alpha^{\;2}}{2}\right) \approx \varepsilon_1\left(1 + \frac{\left(\beta\delta F\right)^2}{2F^{\;4}}\right)$$



- Differential orbit measurements allow seeing focusing errors of 1-2%.
  - It is sufficient to tune the line focusing so that the emittance growth would be below 10%.
  - Further improvement is expected from online tuning with orthogonal quads.

Requirements for dispersion mismatch for MI to Tevatron transfer

$$\varepsilon_2 \approx \varepsilon_1\left(1 + \frac{\left(\sigma_p\delta D_{max}\right)^2}{2\beta_{max}}\right)$$



- Dispersion mismatch below about 0.5 m does not produce significant emittance growth

Emittance Growth due to X-Y Coupling

Emittance growth for beam transfer from an uncoupled lattice with b_x, a_x, b_y and a_y, to a coupled lattice described by b_{1x}, a_{1x}, b_{1y}, a_{1y}, b_{2x}, a_{2x}, b_{2y} and a_{2y} with the eigen-vectors

$$\mathbf{v}_1 = \begin{bmatrix} \sqrt{b_{1x}} \\ -\dfrac{i(1-u)+a_{1x}}{\sqrt{b_{1x}}} \\ \sqrt{b_{1y}}e^{in_1} \\ -\dfrac{iu+a_{1y}}{\sqrt{b_{1y}}}e^{in_1} \end{bmatrix} \quad , \qquad \mathbf{v}_2 = \begin{bmatrix} \sqrt{b_{2x}}e^{in_2} \\ -\dfrac{iu+a_{2x}}{\sqrt{b_{2x}}}e^{in_2} \\ \sqrt{b_{2y}} \\ -\dfrac{i(1-u)+a_{2y}}{\sqrt{b_{2y}}} \end{bmatrix}$$

is determined by the following equations:

$$e_1' = e_1 A_{11} + e_2 A_{12}$$
$$e_2' = e_1 A_{21} + e_2 A_{22}$$

$$A_{11} = \frac{1}{2}\left(\frac{b_x}{b_{1x}}\left[(1-u)^2 + a_{1x}^{\ 2}\right] + \frac{b_{1x}}{b_x}\left[1 + a_x^{\ 2}\right] - 2a_{1x}a_x \right) \quad , \qquad A_{12} = \frac{1}{2}\left(\frac{b_y}{b_{1y}}\left[u^2 + a_{1y}^{\ 2}\right] + \frac{b_{1y}}{b_y}\left[1 + a_y^{\ 2}\right] - 2a_{1y}a_y \right)$$

$$A_{21} = \frac{1}{2}\left(\frac{b_x}{b_{2x}}\left[u^2 + a_{2x}^{\ 2}\right] + \frac{b_{2x}}{b_x}\left[1 + a_x^{\ 2}\right] - 2a_{2x}a_x \right) \quad , \qquad A_{22} = \frac{1}{2}\left(\frac{b_y}{b_{2y}}\left[(1-u)^2 + a_{2y}^{\ 2}\right] + \frac{b_{2y}}{b_y}\left[1 + a_y^{\ 2}\right] - 2a_{2y}a_y \right)$$